The SNS Ion Source

By:

Martin P. Stockli

Table of Contents:

- Introduction
- Ion source information:
  1. The SNS ion source and LEBT
  2. General Utilities
  3. Vacuum and Hydrogen Gas
  4. RF-Power
  5. Plasma
  6. Cesium
  7. Magnetic fields
  8. Electric fields
- Test

Introduction: What is an Ion Source?

- ***Ion Source*** ***i·on source*** *noun*

  device for producing ions: *a device that produces a stream of ions, especially for use in particle accelerators or ion implantation equipment.*

- ***Ion*** ***i·on*** *[ī òn] (plural* ***i·ons****) noun*

  electrically charged atom or atom group: *an atom or group of atoms that has acquired an electric charge by losing or gaining one or more electrons.*

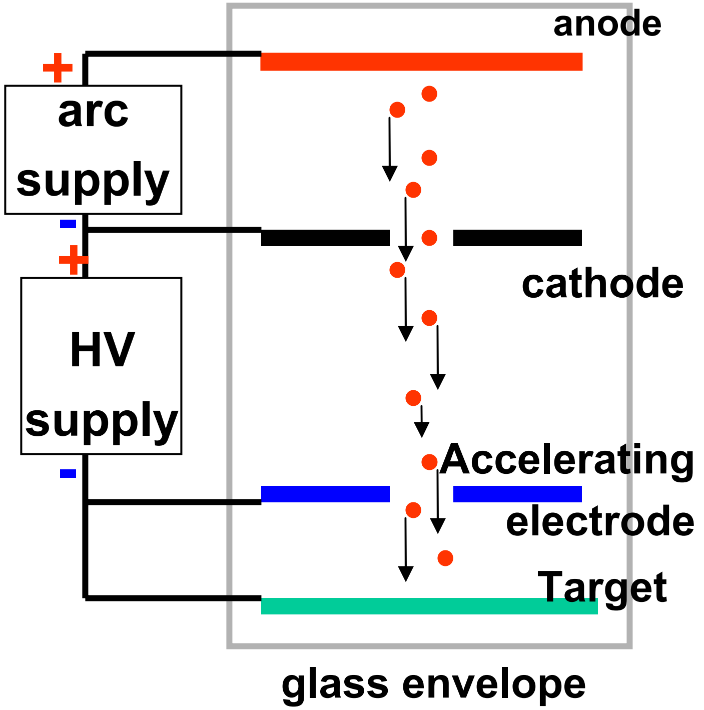
  [Mid-19th century. From Greek ion , literally "moving thing," from the present participle of ienai "to go," from the movement of any ion toward the electrode of opposite charge.]

Encarta® World English Dictionary [North American Edition]
Developed for Microsoft by Bloomsbury Publishing Plc.

Introduction: How were Ions discovered?

- *In the mid-19th century physicists experimented on the conduction of electricity through low pressure gases. Measuring the current while changing the pressure and voltage, rearranging electrodes, and drilling holes in the electrodes, they invented the first ion source when they discovered the positive- or canal-rays coming apparently from the positive electrode.*
- *These positive particles, ions, only emerge from the canal when the arc is operated with sufficient voltage.*

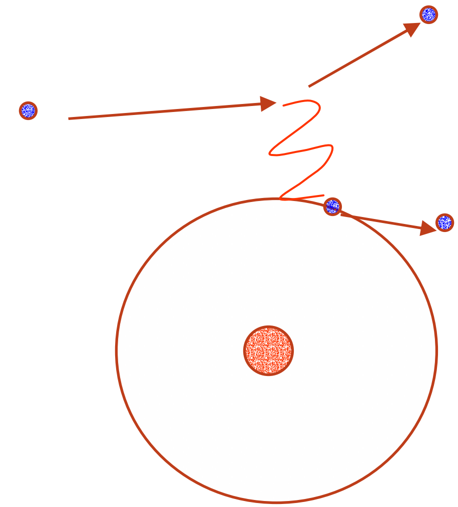
Canal Ray Ion Source



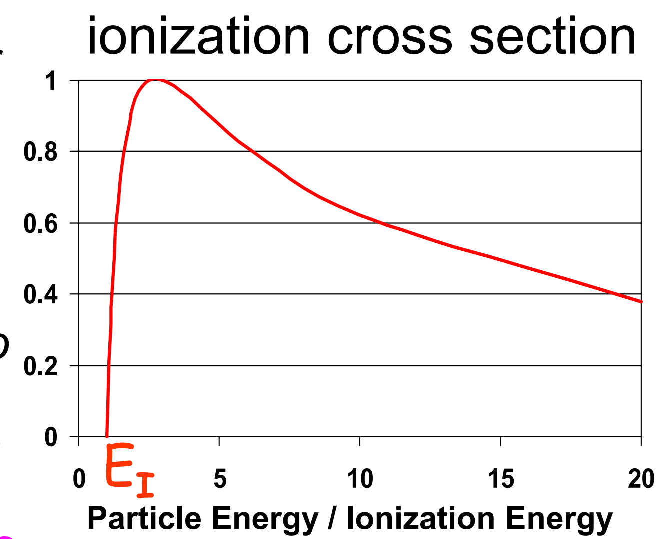
How are the ions generated?

Introduction: How are Ions born?

- *Ionization in gases,* the removal of an electron from an atom or molecule, *requires* an electric field in *excess of 10^{10} V/m,* only possible within atomic distances typically *reached in collisions* with charged particles [$F_C = (4\pi\epsilon_o)^{-1} \cdot q_1 \cdot q_2 / r_{12}^2$].
- *The conservation of energy and momentum favors electrons as the most efficient ionizing particles, and therefore most ion sources use electron impact ionization.*
- *The conservation of energy is responsible for an absolute threshold, the ionization energy E_I, the minimum energy which needs to be transferred for successful ionization.*



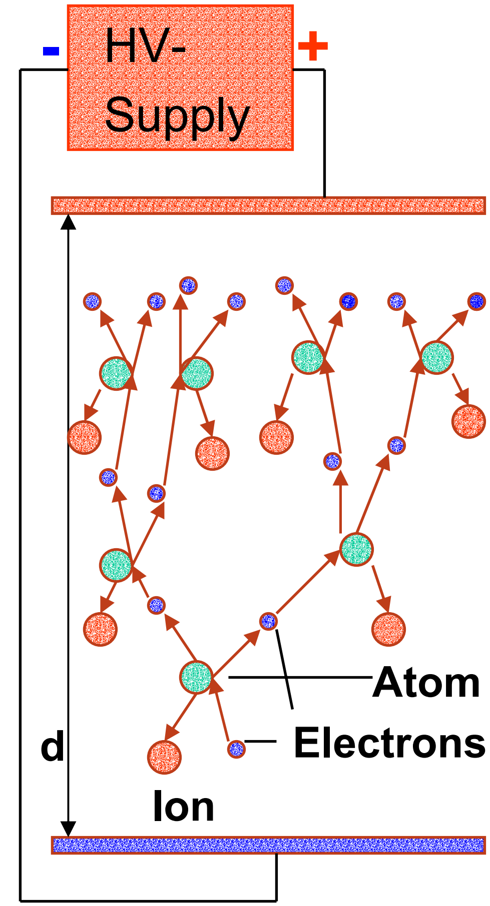
- *Gases have ionization energies between 12.1 eV for O_2 and 24.6 eV for He, e.g. 15.4 eV for H_2 molecules and 13.6 eV for H atoms.*
- *The electron impact ionization cross sections are typically 10^{-16} cm², roughly the size of the atoms.*
- *The ionization cross section has a maximum close to 3 times the ionization energy E_I and therefore electrons with an energy between 50 and 100 eV can ionize all gases efficiently.*



But how do we get a lot of ions ??

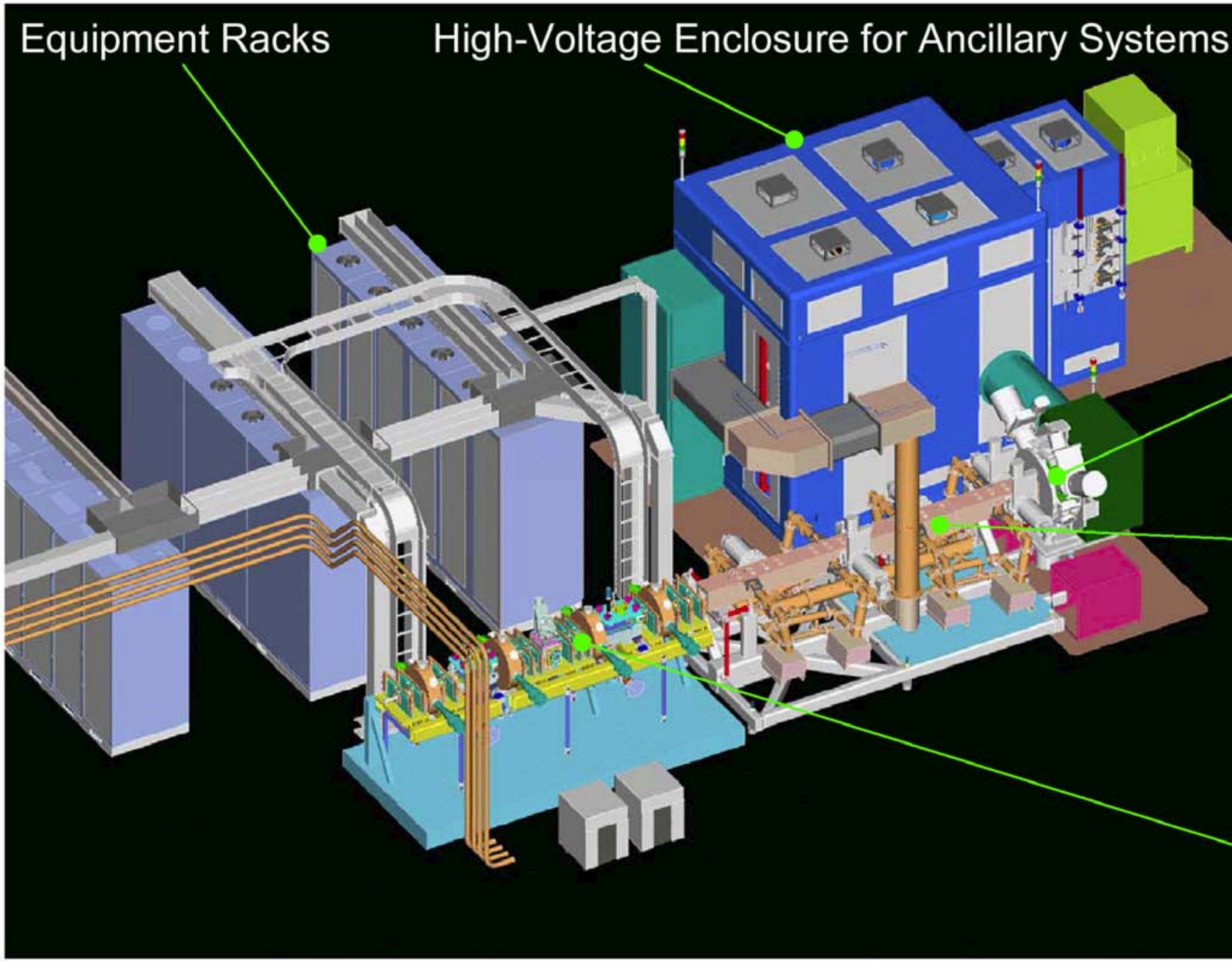
Introduction: How do Ions multiply?

- Ionization rates can be increased with discharges.
- Townsend discharges occur when the electric field and the gas pressure allow free electrons to gain energy in excess of the ionization energy between two subsequent collisions (mean free path for ionization λ_i.
- As the ionizing electron and the ionized electron both (re-)gain enough energy and ionize again, they start an avalanche. The resulting discharge current grows exponentially with d, the gap between the anode and cathode, if the voltage is increased proportional to d.
- Keeping the electrode gap d constant, and varying the pressure, the discharge current will reach a maximum when the average energy cost per ionization is minimum at the Stoletow point: p_{opt}[Torr] = E[V/m] /35,000 for H_2, This means that the minimum average energy cost per ionization is 33 eV for H_2 .



Lets move on !!

1: The SNS ion source and LEBT



Ion Source/LEBT
65 keV Create 50-mA H⁻ ion beam

RFQ
Accelerate beam to 2.5 MeV

LEBT/ MEBT
Chop beam into mini-pulses

MEBT
Match 40-mA beam into DTL

In the Front-end building on Chestnut-Ridge !!

2: Utilities

The following utilities are needed:

- AC Power produces heat
- Cooling water removes the heat
- Compressed air removes the heat and operates pneumatic equipment

Do not try to operate the Ion Source / LEBT without all three utilities !!

3: Vacuum and H_2 Gas

•To generate H^- ions, H_2 gas needs to be injected into the source.

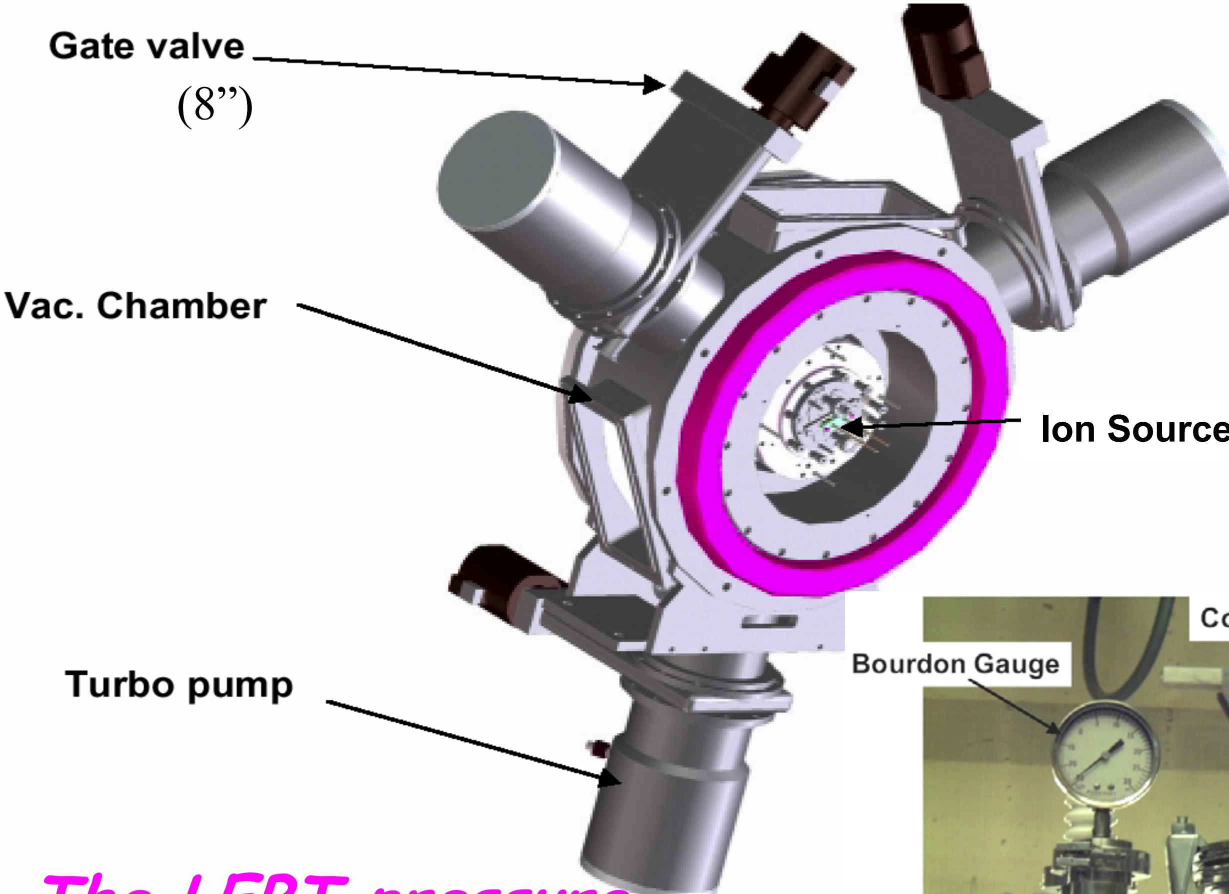
•The SNS ion source has gaps of a few cm, featuring the highest discharge current at a fraction of a Torr. The highest extracted ion currents, however, are found at substantially lower pressures. The SNS ion source operates at 20-30 mTorr, a particle density n_p of $10^{15}cm^{-3}$ or 0.003 % standard atmospheres.

•The non-ionized, neutral particles with density n_p and mass m randomly collide with each other and the walls. For a wall temperature T (in °K) the average particle velocity is $v_p = (8kT_p/\pi m_p)^{1/2}$, with H_2 at 1.1 miles/s being about 4-times faster than N_2.

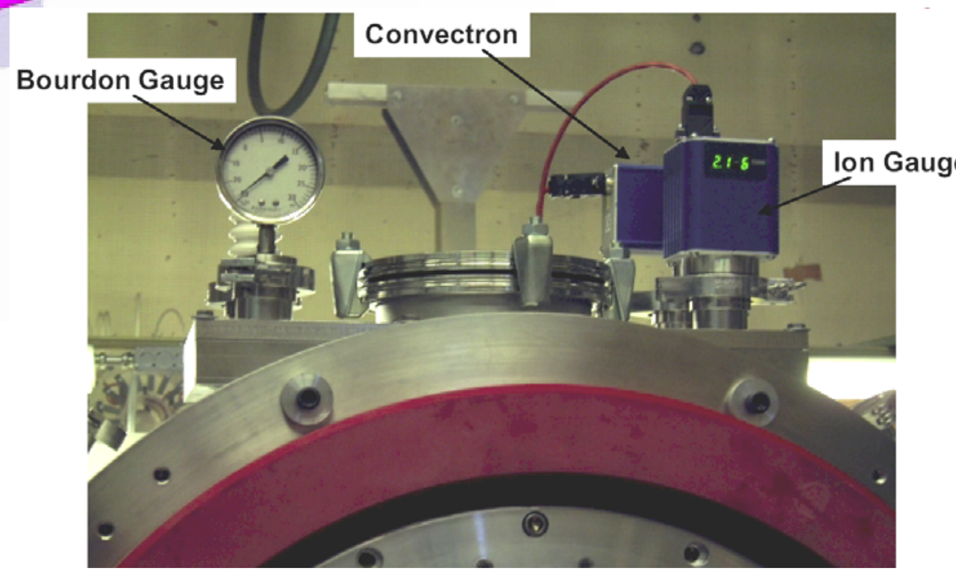
•Ion sources need an opening to extract the low-energy ions. The SNS ion source has a 7 mm diameter, circular extraction aperture with a 0.38 cm^2 area. Through this area A, neutral particles escape at a rate of $Q = \frac{1}{4} v_p n_p A$, which is about 10^{19}pps from the SNS ion source, or **about 1,000 neutrals for each extracted ion.** The pressure is maintained by adding about 1 Torr•ℓ/s Hydrogen gas.

Where do the 1000 neutral particles per ion go ?

3: Vacuum pumps & gauges

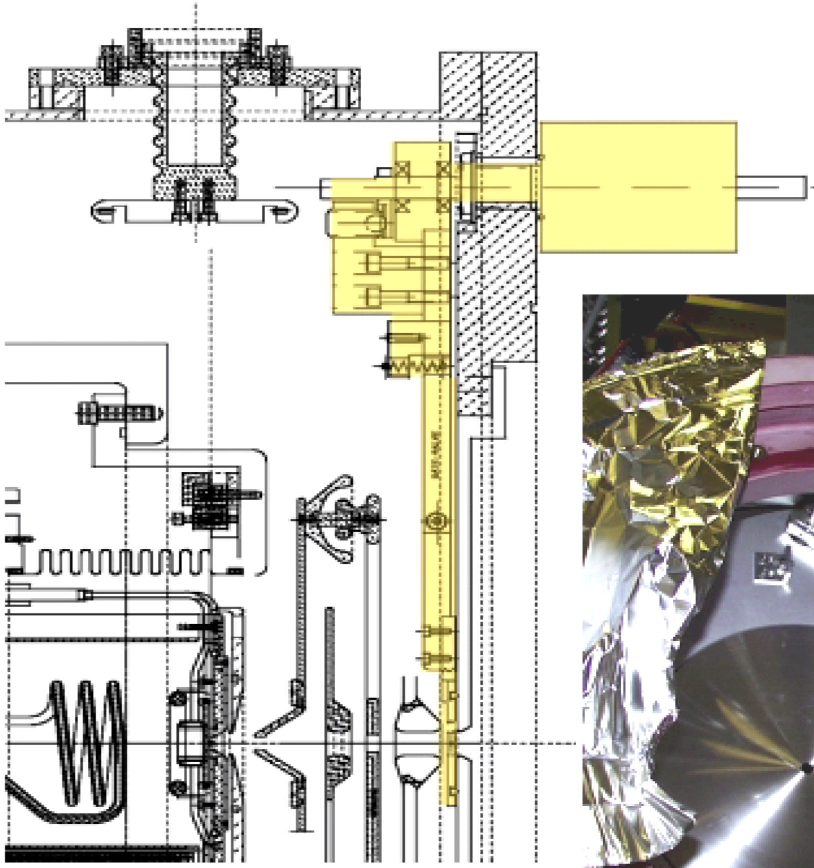


- To limit the charge-exchange to 10%, the neutral particles are removed from the LEBT by 3 pumps with a speed S_p = 1500 l/s.
- The LEBT pressure P_L is $P_L = Q/S_p$

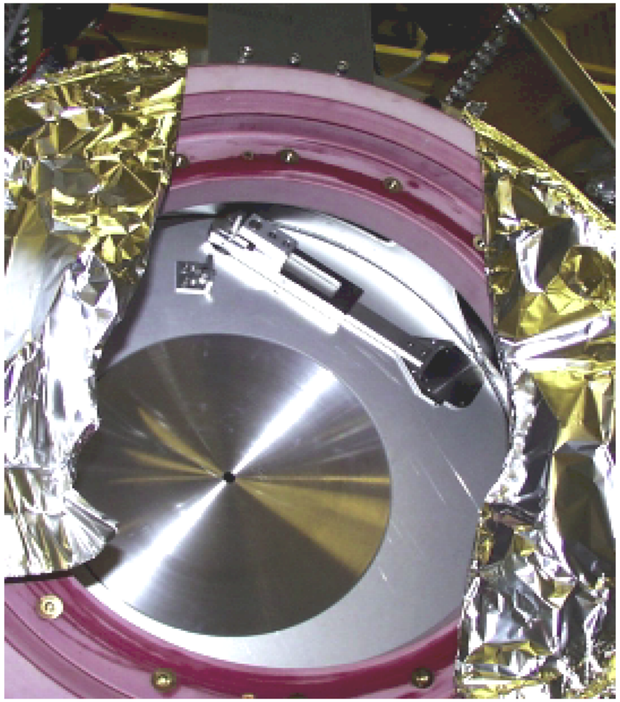


The LEBT pressure is the crucial monitor:
No gas: ~ 10^{-6} Torr
With H_2 gas ~ 10^{-4} Torr

3: LEBT vacuum isolation valve



Needed to isolate the LEBT from the RFQ when venting the LEBT to replace the ion source !

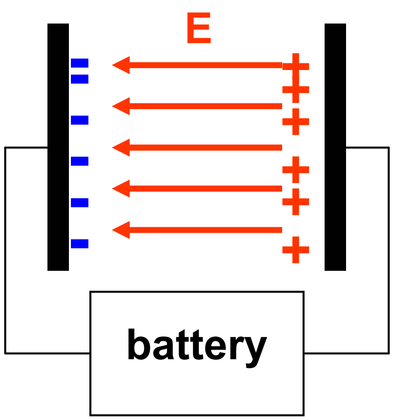


Under development!!

Watch the pressure gauges when venting !!

4: RF -- why?

- The 1st Maxwell Equation: $\nabla \cdot E = \rho/\epsilon_o$ states that electric fields are generated by any free net charges and the easy controllable surface charges ρ on electrodes. This explains the need for the surface charges to generate the required electric field. As the negative surface charges attract positive ions the sputtering problem appears unavoidable.

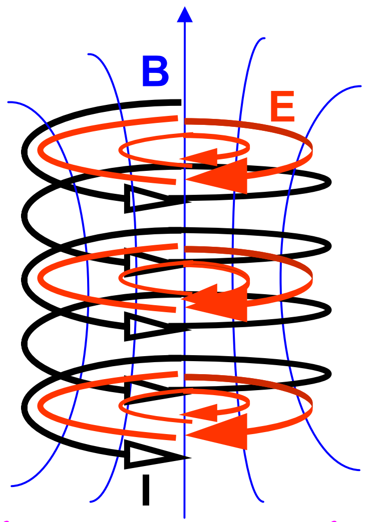


- The 2nd Maxwell Equation, however, $\nabla \times E = -\partial B/\partial t$ describes a curling E field generated by a changing magnetic field in absence of any charge!

A changing magnetic field B can be produced with an alternating current $i = i_o \cdot \cos(\omega t)$ in N windings with radius r_o: $B = \frac{1}{2} \cdot \mu_o \cdot N \cdot i / r_o$ (Biot-Savart).

Now integrate Maxwell's 2nd equation for Faraday's law: $\int \mathbf{E} \cdot d\mathbf{s} = -d\Phi_B/dt = -d/dt \int \mathbf{B} \cdot d\mathbf{A}$

and solve for E: $E(r,t) = \frac{1}{4} \cdot r/r_o \cdot \mu_o \omega N \cdot i_o \cdot \sin(\omega t)$



This is a circular electric field that bites its own tail rather than a poor electrode!

Antenna current i_o is the crucial parameter!

4: optimizing antenna current

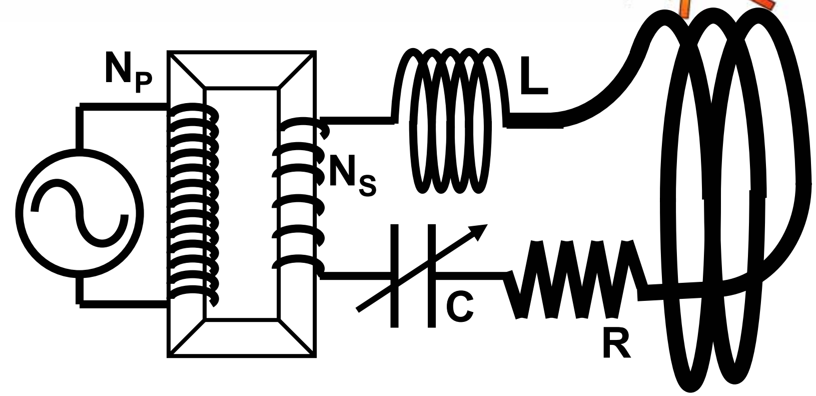
•The output impedance of the RF amplifier is matched to the antenna network impedance by adjusting the transformer ratio N_S/N_P.

•The antenna/plasma RLC circuit has a resonant frequency of $\omega^2 = (LC)^{-1}$ and an impedance $Z = \mathcal{E}_o/i_o = (R^2 + (\omega L - (\omega C)^{-1})^2)^{½}$

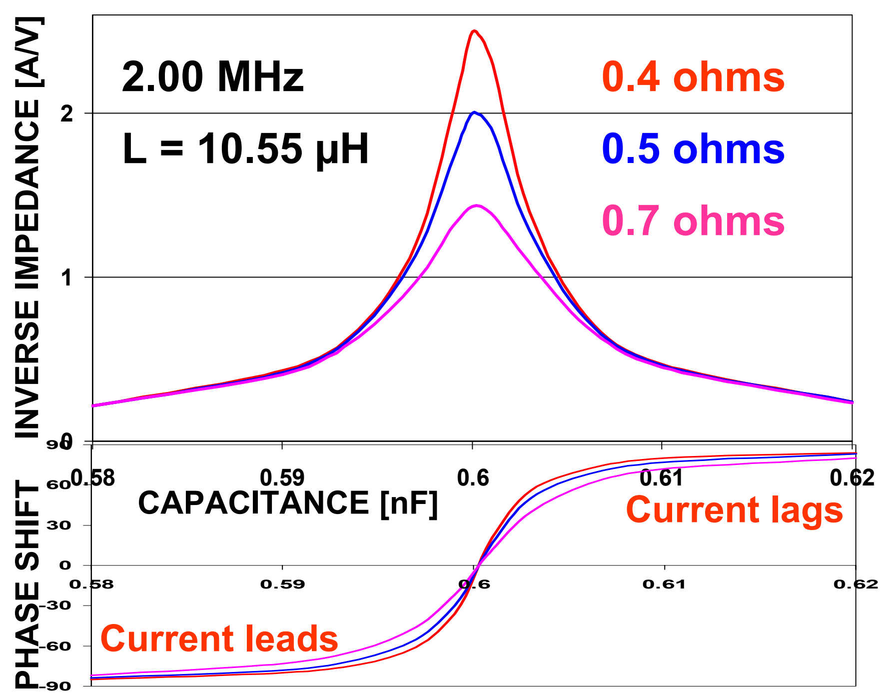
•With $L \approx 10\ \mu H$ and $\omega \approx 2 \cdot \pi \cdot 2$ MHz we need to tune C around 0.6 nF until we obtain the maximum current $i_o = \mathcal{E}_o/R$.

•If needed the resonance can be located with the phase shift.

Optimize antenna current by keeping resistance low and optimizing tune with capacitor C !



ANTENNA CURRENT versus CAPACITANCE



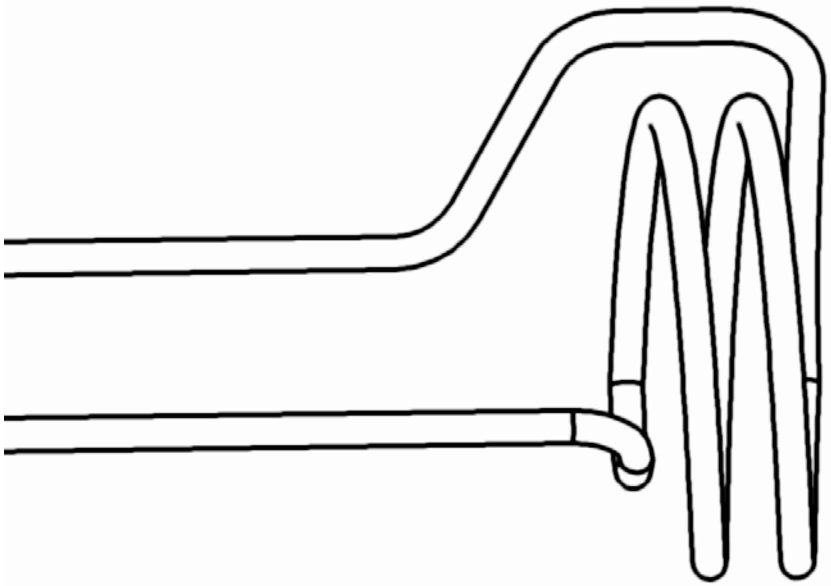
August 2002

4: RF hazards !!

- The antenna is a coil with N turns of radius r_o. The ratio between the total enclosed magnetic flux Φ_B and the current is the definition of the inductance $L = \Phi_B/i = N \cdot B \cdot \pi \cdot r_o^2/i = ½ \cdot \pi \cdot \mu_o \cdot r_o \cdot N^2$

  For $r_o = 33$ mm, N=2½:

  $L = 0.4\ \mu$Henry



The induced voltage is $\epsilon_L = - L \cdot di/dt = \omega \cdot L \cdot i_o \sin(\omega t)$.

For 2 MHz: $\epsilon_L = 5 \cdot i_o[A] \cdot \sin(\omega t)$

The induced voltage becomes significant as we crank up the RF power to increase the ion current output, e.g. 1.2 kV peak with 240 A when delivering 34 kW RF power.

The induced voltages are personnel- and equipment-hazards !

5: Plasma

To produce enough ions we need to generate a plasma, easily recognized!

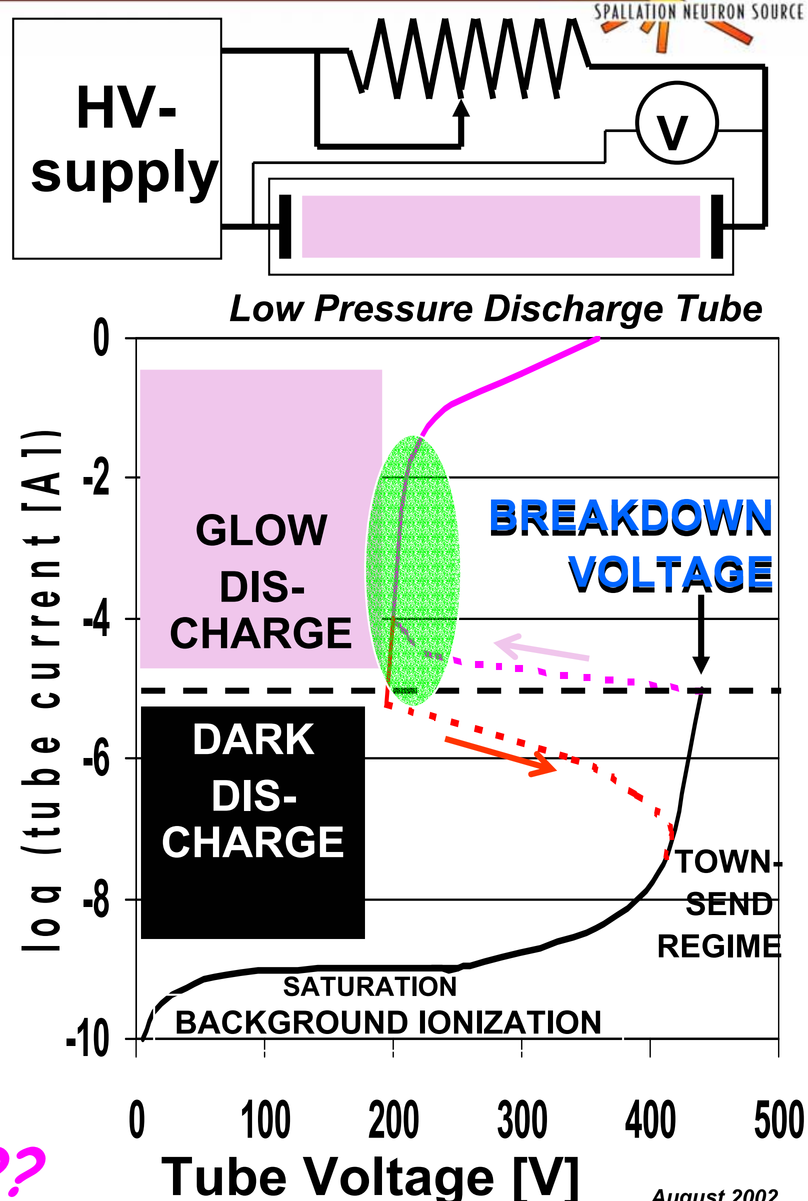
This photo shows an inductive coupled plasma generated with 13 MHz RF being applied to the SNS-style, 2½ turn antenna mounted in our test dome. The test dome has the same size and the same electrical and magnetic boundary conditions as the plasma chamber of the SNS ion source. The test dome allows observing the plasma but not to extract ions.

The curling E-field is induced by the solenoidal antenna loops with the highest ionizing field close to the antenna. This is well suited for producing plasma in a large volume which can easily be confined with a multicusp magnetic field.

Light is the crucial parameter !

5: Plasma, a low pressure discharge

- Applying a small voltage to a discharge tube typically results in nA's of current produced by background ionization.
- When the voltage is raised significantly the current starts to grow exponentially up to many µA due to Townsend multiplication and the onset of corona.
- Further increasing the voltage, suddenly the current grows up to many mA and the gas starts to glow at a much reduced voltage. The glow discharge is maintained and amplified by secondary electrons emitted when the ions impact on the cathode.
- As the glowing plasma covers a growing fraction of the volume, a growing voltage increase is needed to increase the current, but most ion sources operate at low pressures.



How do we start the plasma ??

5: Plasma Breakdown Voltage

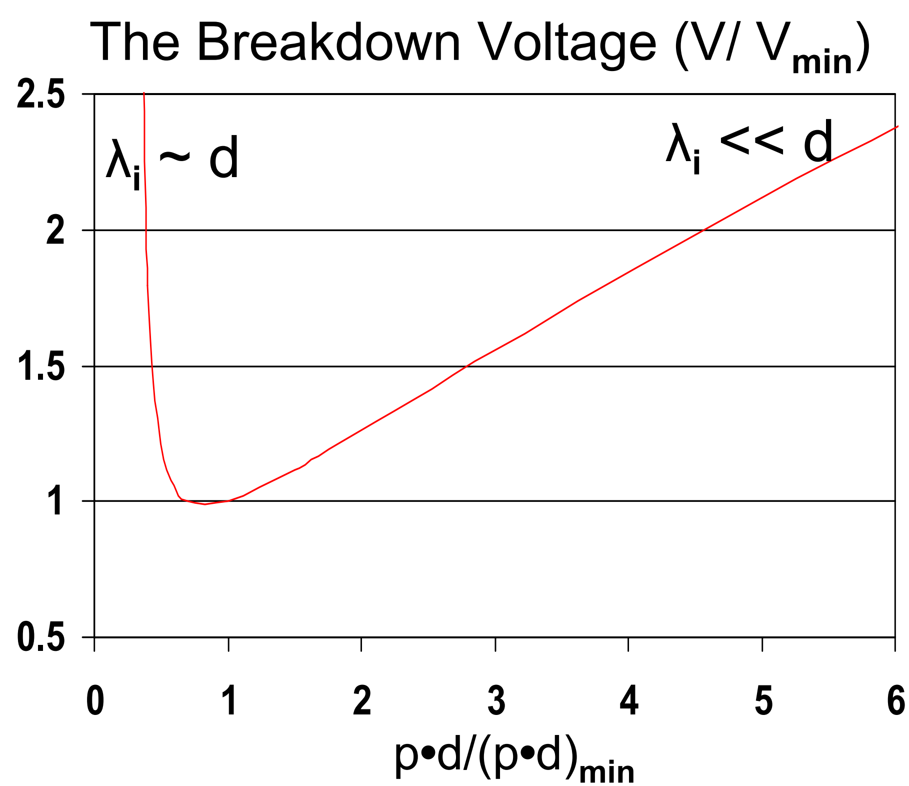
•The voltage at which a low pressure gas breaks down depends only on the ratio of the electrode gap d and the mean free path for ionization λ_i, or p•d, the product of gap d and the pressure p.

•The minimum voltage and corresponding p•d depend on the gas and secondary electron emission coefficient of the cathode material.

Gas	Cathode	V_{min} (V)	$(p•d)_{min}$ (Torr•mm)
Air		360	15
H_2	Pt	295	12.5
He	Fe	150	25

•No breakdown occurs at very low pressure and at very high pressure.

•Therefore, the ion source is started by first applying the RF followed by temporarily increasing the gas pressure until the plasma starts.



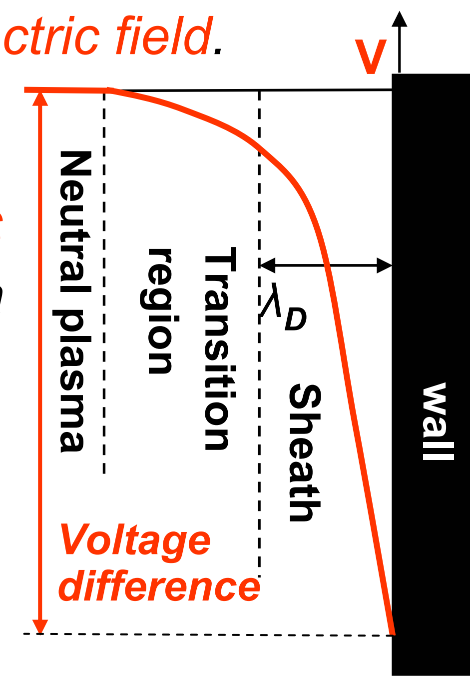
5: some Plasma physics

•A plasma is composed of neutrals, electrons and ions with densities n_n, n_e, and n_i, typically in the range between 10^{10} to 10^{16} particles per cm^3 corresponding to a **pressure between** 10^{-6} and 0.1 Torr.

•The repulsive nature of equal charges requires that essentially all plasmas are practically neutral (quasi-neutral): $e \bullet \Sigma Q_i \bullet n_i = e \bullet n_e$

•Plasma physics dominates if degree of ionization $n_i/(n_i+n_n)>0.1$.

•The average particle speed is $v_p = (8kT_p/\pi m_P)^{1/2}$ with $T_e \geq T_i > T_n$, which means $v_e \geq 43 \bullet v_i$. The rapidly moving electrons leave behind the ions and their space charge creates a or modifies the existing electric field.

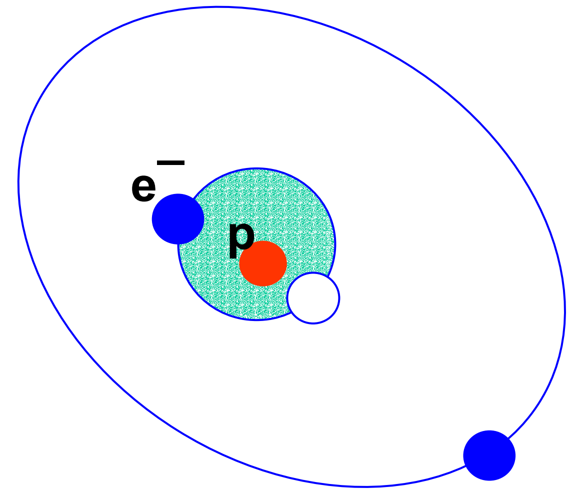


•Charges interact with other charges only within a distance λ_D, the Debye length: $\lambda_D^2 = \epsilon_o kT_e/e^2 n_e$ or $\lambda_D\,[cm] = 743\,(T_e[eV]/n_e[p/cm^3])^{1/2}$ (A few μm for the SNS ion source). The surface charges on electrodes create a plasma sheath with a thickness λ_D which maintains most of the potential difference between electrodes.

•The plasma frequencies are $f_P^2 = n_p \cdot e^2/(4\pi^2 \epsilon_o m_P)$. The SNS ion source has plasma frequency of ~ 100 GHz for the electrons and ~ 2 GHz for the ions and hence the RF interacts with the individual particles.

6: Cesium, the negative ion helper

- Hydrogen atoms have one proton and one electron and hence an open shell. Therefore they can attract an extra electron and form a stable ion with a net charge of –e.



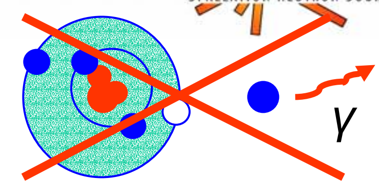
- The stability is quantified by the electron affinity, the minimum energy required to remove the extra electron, which is only 0.75 eV compared to the 13.6 eV ionization energy.
- For electron energies above 10 eV, the H^- ionization cross section is ~ $30 \cdot 10^{-16}$ cm^2, 30 times larger than for H_2 molecules !
- For H^+ energies below 1 keV, the recombination cross section is larger than $100 \cdot 10^{-16}$ cm^2.

H^- ions are fragile !

- Charged particle collisions destroy H^- ions easily!!

6: So how are H^- ions born?

•Conserving energy when forming a negative ion through direct electron attachment, the excess energy has to be dissipated through a photon. $A + e = A^- + \gamma$

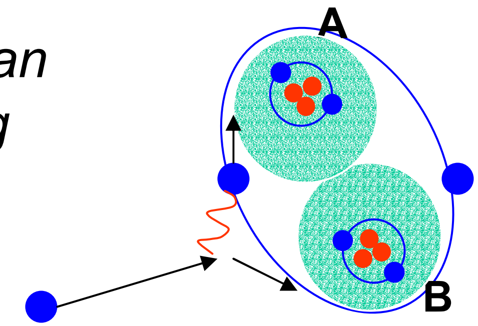


But Radiative Capture is rare ($5 \cdot 10^{-22} cm^2$ for H_2).

•More likely are processes where the excess energy can be transferred to a third particle, e.g. when dissociating a molecule (4.5 eV for H_2): $M + e = A + B + e$

and sometimes $= A + B^-$

($\sim 10^{-20} cm^2$ for H_2 and $E_e > 10$ eV)

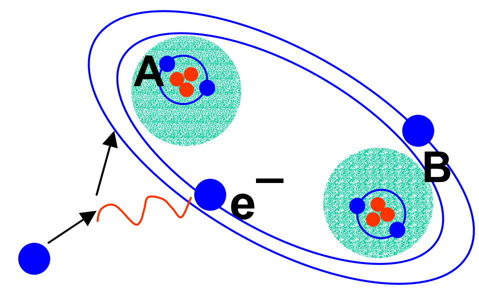


•Most likely are processes which excite a molecule to the edge of breakup (vibrationally excited $4<n<12$)

$M + e(fast) = M^* + e$

and then dissociated by a slow electron

$M^* + e(slow) = A + B^-$



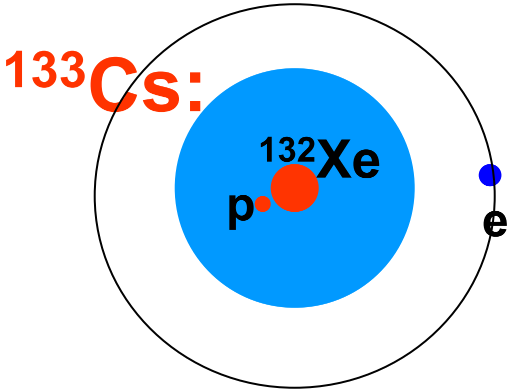
But the frequency of 2-step processes is limited!

The small electron affinity causes the production of negative ions to be unlikely, but their destruction to be likely !!

H^-, a rare specie!

6: Cesium, the negative ion helper

- Cesium has 55 protons, ~78 neutrons, and 55 electrons.
  - This is like the noble ^{132}Xe plus 1 proton plus 1 electron and therefore the last electron is very loosely bound with only 3.9 eV ionization energy. Cs is easily ionized.



A little Joke:

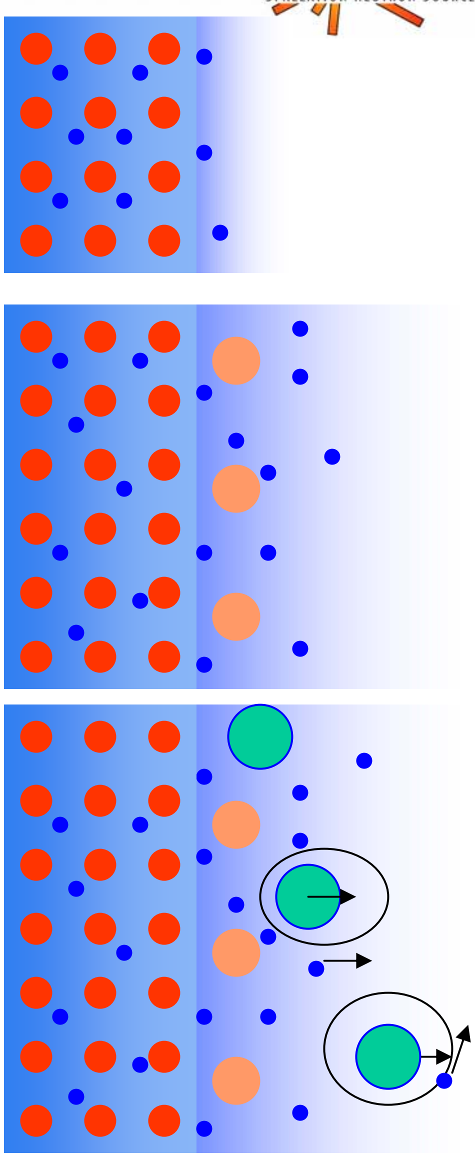
Two Cesium atoms are walking down the street. Says the first Cesium atom, "oh my god! I think I'm missing an electron". Says the second, "are you sure?" Says the first, "I'm positive".

- The Cesium ionization energy greatly differs from the 0.75 eV electron affinity of H^-, and therefore H atoms are **VERY unlikely** to capture the outer electron from Cs.

So how can Cs be used for H^-?

6: Cesium, the negative ion helper

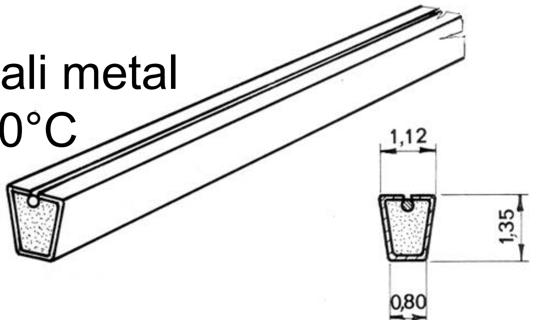
- *Metals host an abundance of loosely bound electrons (conduction electrons) but it takes about 4.5 to 6 eV to remove an electron from the surface (called work function).*
- *Cesium, a liquid metal at room temperature, has a work function of 2 eV only. But when condensed on a cold metal surface, Cs can lower the surface work function even further to 1.4 to 1.8 eV when covering about 60% of the surface (0.6 mono-layers).*
- *Atoms with an electron affinity in excess of 2 eV can easily pick up an electron and form an negative ion when desorbing from the surface.*
- *An experiment points to H^- being formed mostly by desorbing H atoms. But this requires the H atoms to transfer about 1 eV energy to the electron while leaving the surface. Theory suggests H^- being formed by fast ions reflecting from the surface.*



Who cares, we know it works very well !!

6: Cesium, the negative ion helper

- **A collar close to the extraction aperture contains Cesium Dispensers by SAES**
- The dispensers contain a mix of alkali metal chromates (Me_2CrO_4) with a reducing agent (St101®) to provide sources of small amounts of alkali metals. The reducing agent also prevents active gases which are produced during the reduction reaction from contaminating the alkali metal vapor.
  - Chromate and reducing agent mixture is held within a nichrome metal container having a trapezoidal cross section with a slit to allow evaporation of the alkali metal. A metal wire partially obstructs the slit to eliminate escape of loose particles.
  - Heating under vacuum is required to activate alkali metal dispensers. Maximum degassing temperature500°C



To coat the surfaces with Cesium, the Cesium Collar needs to be heated with the plasma. After sufficient Cesium is released, the collar needs to be air cooled.

7: Magnetic fields

Charged particles move unimpeded in the direction of a magnetic field.

Particles with mass m, charge q, and velocity v perpendicular to the magnetic field B, undergo a circular motion with radius $r = mv/qB$.

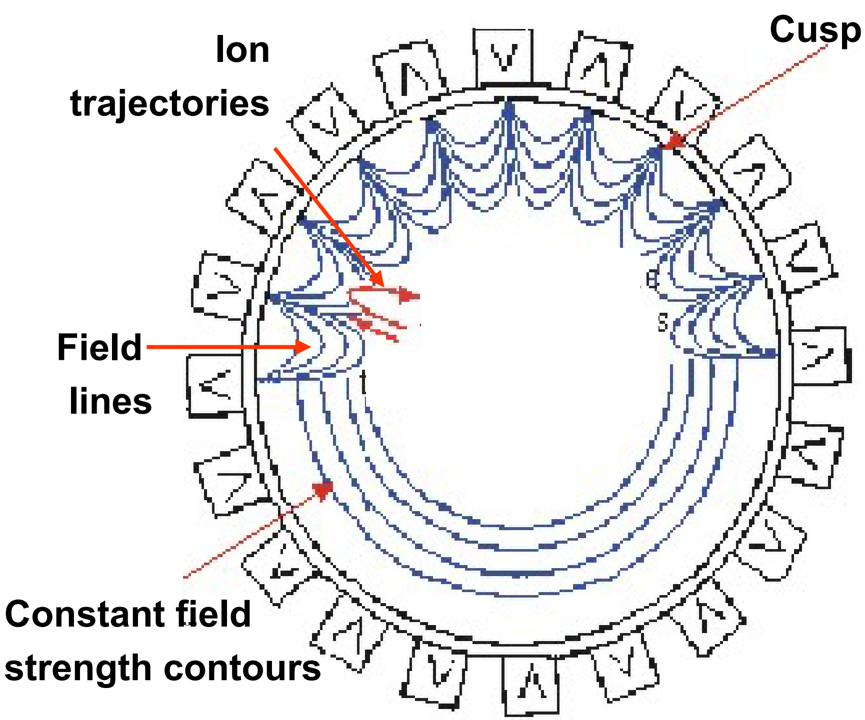
e.g: if B=1 kG, for 10 eV electrons r=0.1mm, for 1 eV protons r = 1.4mm.

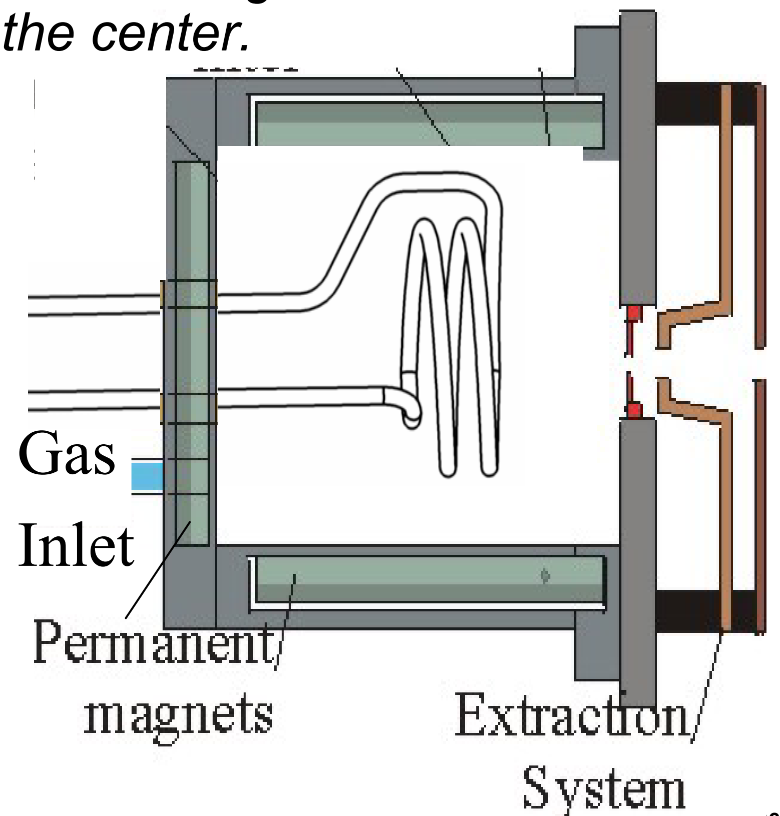
The resulting helical particle motion reduces the wall losses of the ions and electrons.

Therefore magnetic fields are used to confine plasmas.

7: Magnetic fields

- The SNS ion source uses a multicusp field, generated by strong permanent magnets (NdFeB) mounted very close to the vacuum.
- This magnetic field decreases with the distance from the wall, and is zero on the axis,a minimum field configuration.
- The strong magnetic field at the wall acts as a magnetic mirror which returns most ions and electrons back to the center.

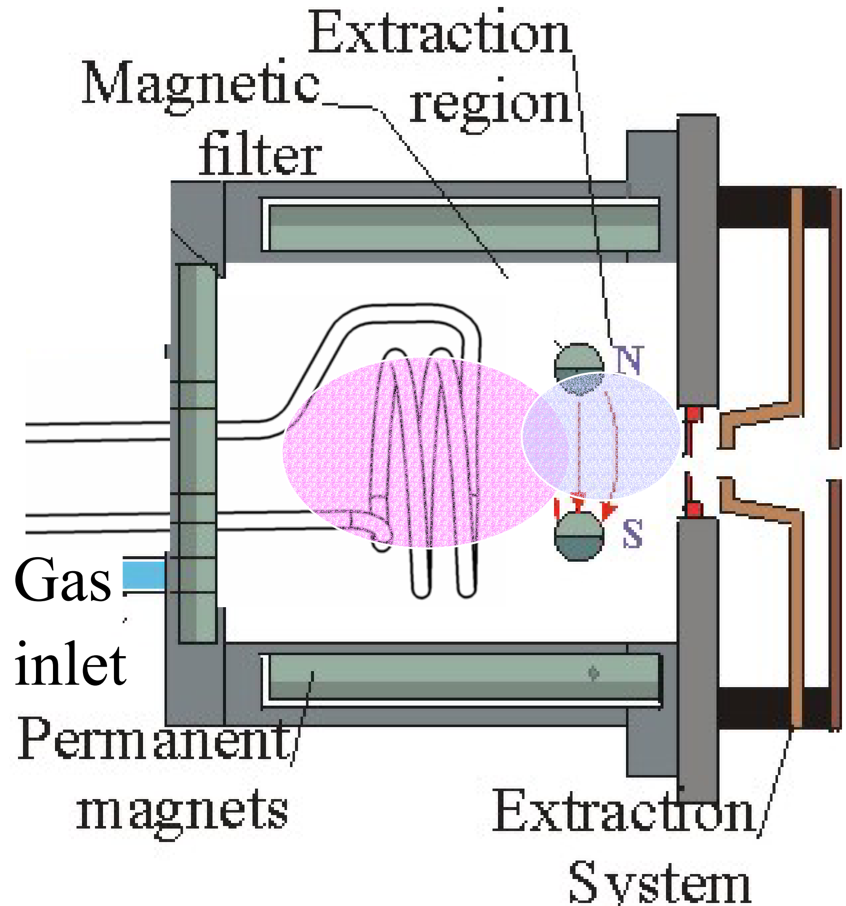




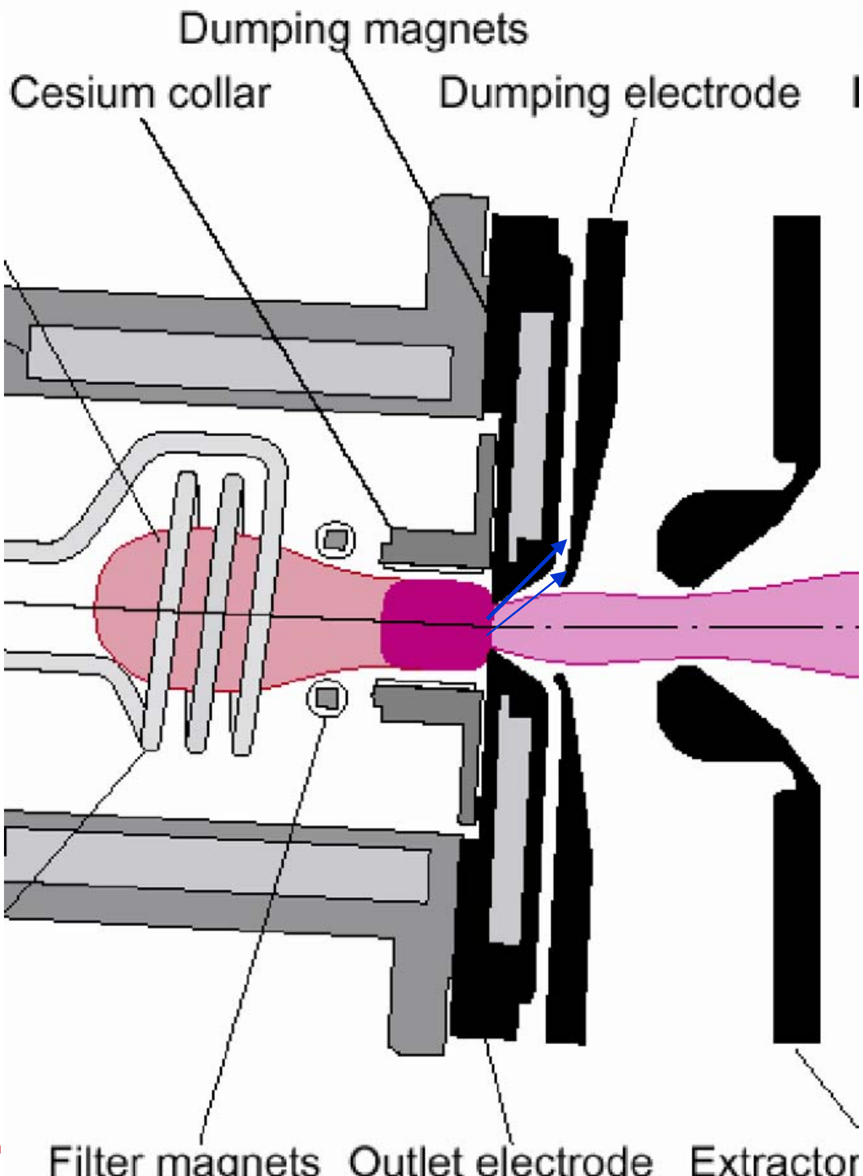
7: Magnetic fields

A dipole filter magnet of a few hundred Gauss protects the negative ions in the cold extraction plasma from the hot electrons in the plasma core.

- The main plasma driven by the RF field generates hot electrons which efficiently excite and ionize atoms and molecules. This hot electrons are reflected by the filter field, e.g. in a 200 Gauss field a 25 eV electron turns around on a 0.03 mm radius.
- Cold electrons and cold ions undergo many, many collisions with other cold charged particles, resulting in a diffusion process which favors the cold charged particles (~$T^{-½}$) and therefore the electron temperature decreases exponentially through the filter- and extraction region.
- Exited neutral molecules migrate freely to the extraction region.



7: Magnetic fields

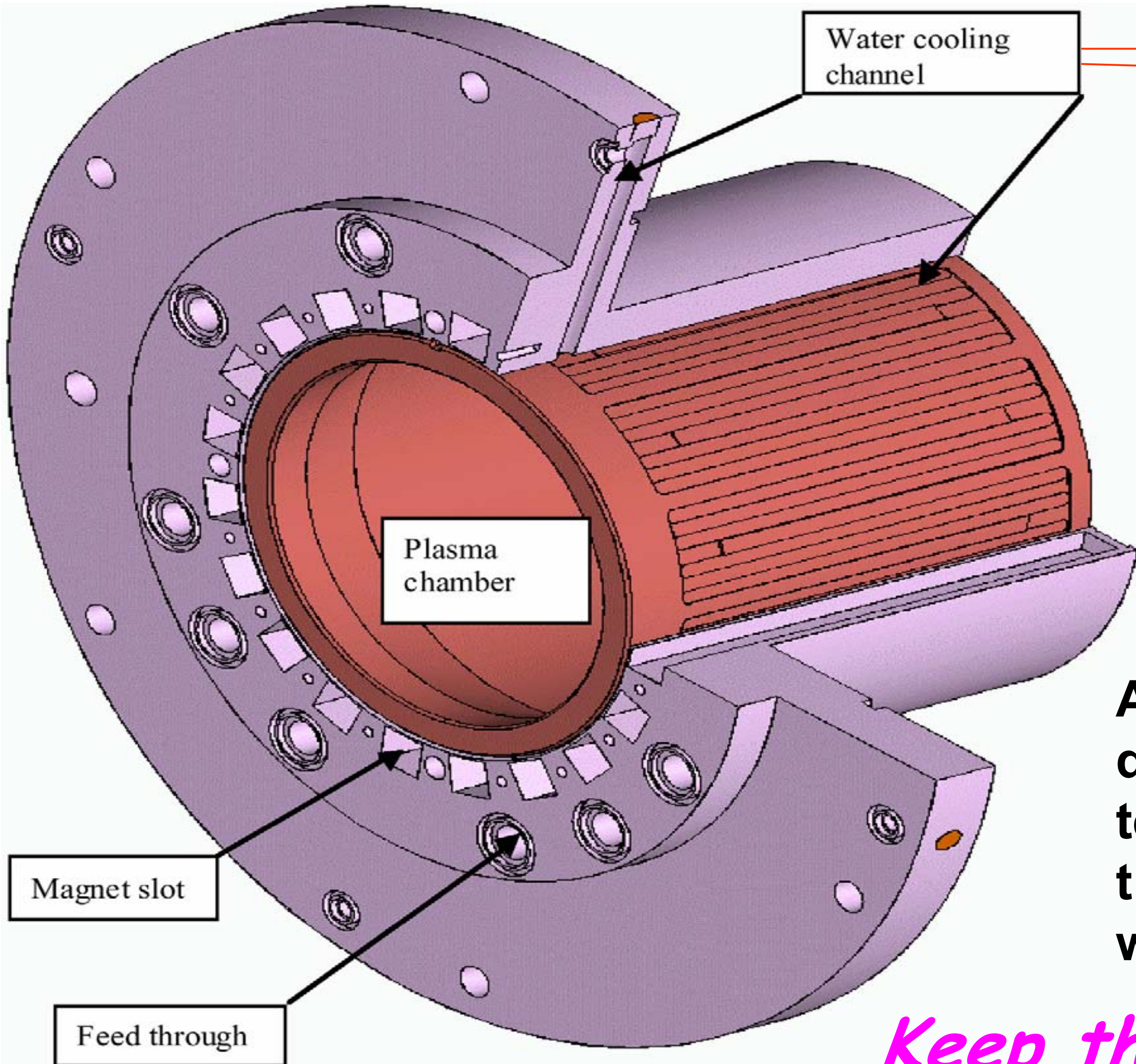


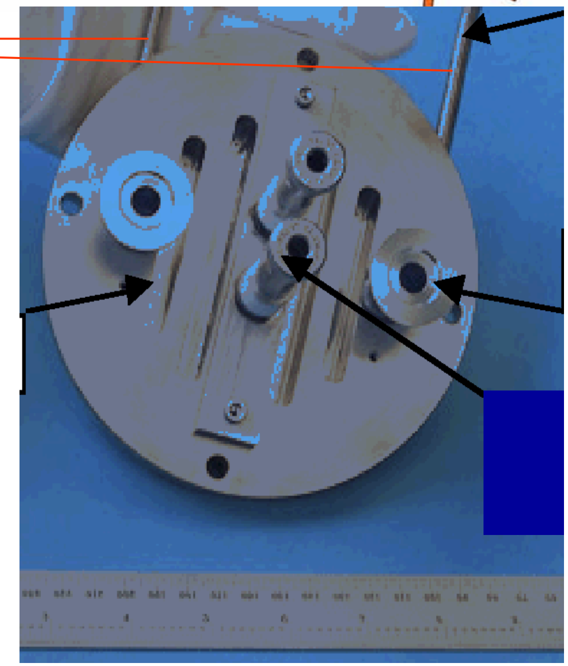
A very strong magnetic dipole field in the extraction aperture is generated by the Hallbach-type permanent dumping magnet.

The magnetic dumping field deflects the electrons strongly and guides them towards the dumping electrode.

The magnetic dumping field deflects also the negative ions, and therefore the ion is tilted by a few degree to allow the ions to end up on axis.

7: Preserving the magnetic fields





All permanent magnets demagnetize at high temperature and therefore have to be water cooled.

Keep the magnets cool !!

8: Electric fields

Electric fields are essential to extract the ions from the plasma and to inject them as a converging beam into the RFQ!

1. ***Source voltage, normally - 65 kV, determines the final ion energy main control for extraction field***
2. ***e-Dump voltage, ~ +7 kV to attract electrons, affects ion extraction***
3. ***Extractor voltage, normally + few kV, does not affect final ion energy, contributes to the extraction field***
4. ***Lens 1, normally ~ –45 kV, does not affect final ion energy***
5. ***Lens 2, normally ~ –45 kV, does not affect final ion energy***

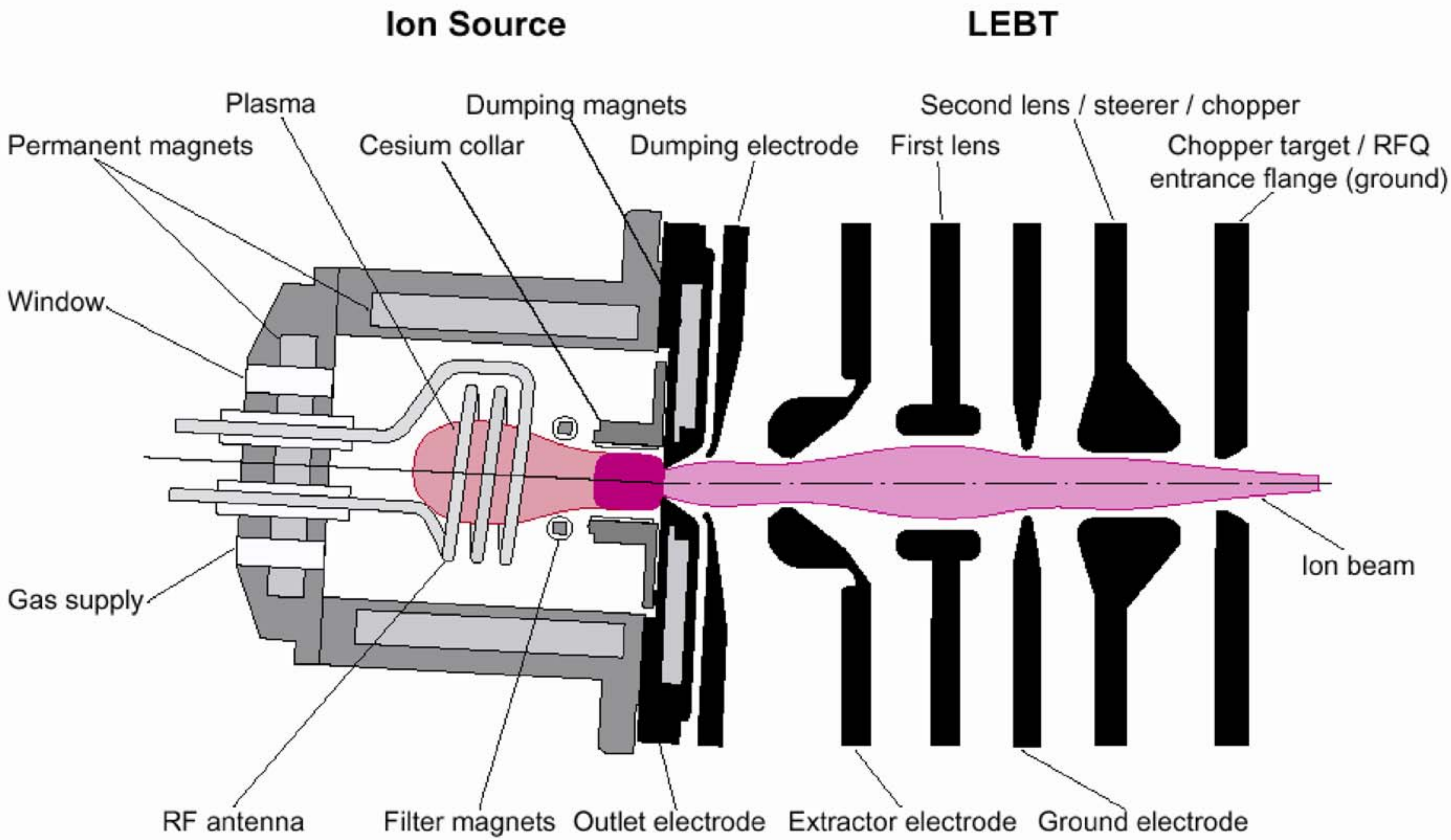
   varying the two lenses displaces the beam waist axially, and changes the waist diameter and convergence angle. (Telescope)

6. ***Horizontal steerer voltage, integrated into segmented lens 2***
7. ***Vertical steerer voltage, integrated into segmented lens 2***

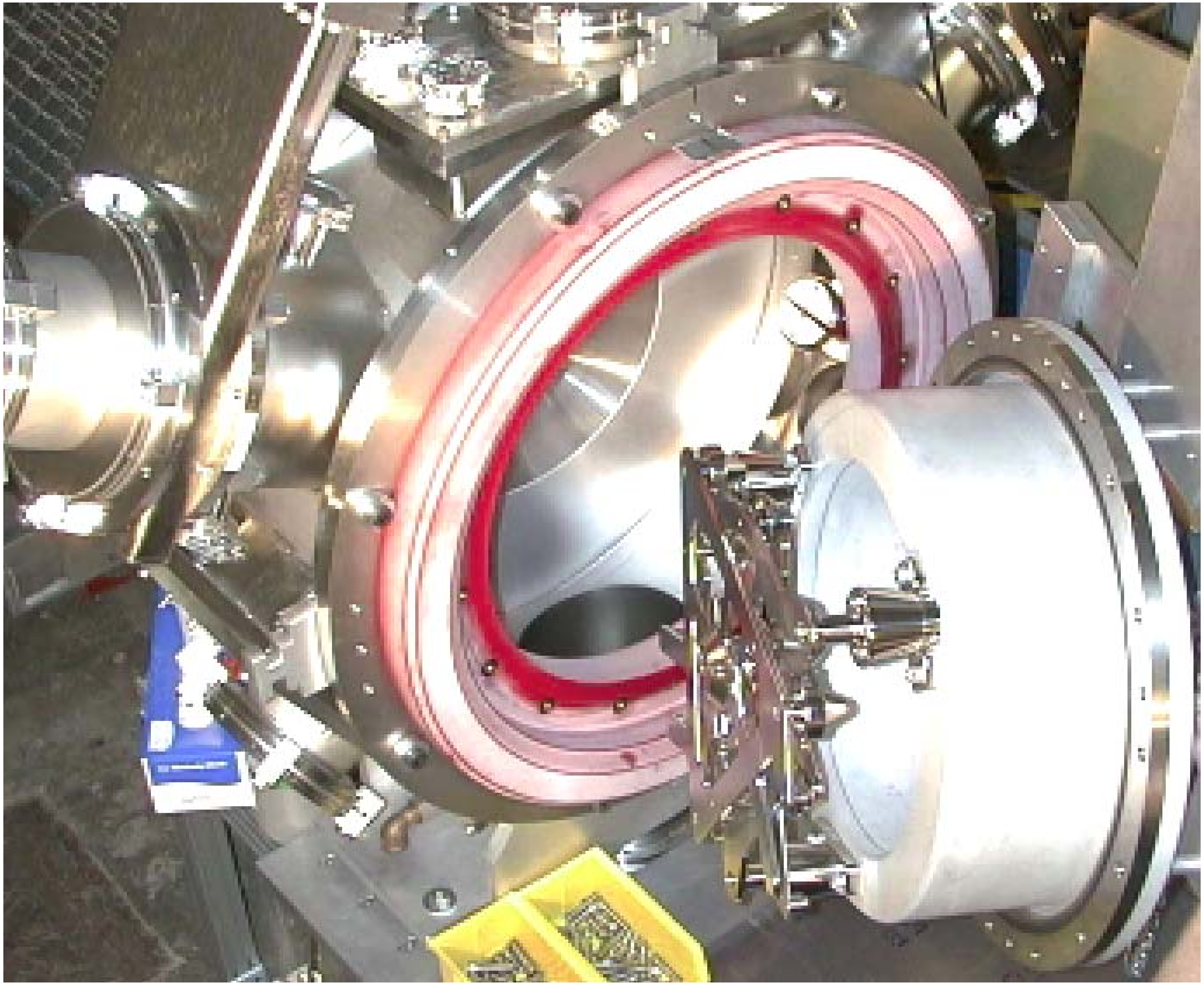
   varying the steerer voltage displaces the beam in horizontal and vertical direction

8. ***Chopper voltage, integrated into segmented lens 2, displaces the beam so much that it misses the RFQ entrance aperture***

8: Electric fields



8: Electric fields



The SNS LEBT is very compact, producing very high electric fields!

Keep it clean !!

For further reference you may want to read:

Below are 10 titles sorted in bestselling order:

1. **Ion Sources,** *Huashun S. Zhang,Jianrong Zhang, Springer-Verlag, 2000, $119.00*
2. **Electron Beam Ion Sources and Traps and Their Applications,** *Krsto Prelec, Springer-Verlag, 2001*
3. **Electron Cyclotron Resonance Ion Sources,** *R. Geller, IOP Pub, 1996, $210.00*
4. **Focused Ion Beams from Liquid Metal Ion Sources,** *P. D. Prewett,G. L. Mair, Wiley, 1991*
5. **Handbook of Ion Sources,** *Bernhard H. Wolf, CRC Press, 1995, $194.95*
6. **International Symposium on Electron Ion Beam Sources and Their Applications,** *Ady Hershcovitch, American Institute of Physics, 1989, $85.00*
7. **Physics and Technology of Ion Sources,** *Ian G. Brown, Wiley, 1989.*
8. **Polarized Ion Sources and Polarized Gas Targets,** *L. W. Anderson, American Institute of Physics, 1994, $288.00*
9. **Polarized Proton Ion Sources,** *G. Roy & P. Schmor, American Institute of Physics, 1983, $37.00*
10. **Polarized Proton Ion Sources,** *Alan D. Krisch & A. M. Lin, American Institute of Physics,1981, $30.00*

From http://shop.barnesandnoble.com